

Theoretical Models of Gamma-Ray Bursts¹

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Abstract. Models of gamma ray bursts are reviewed in the light of recent observations of afterglows which point towards a cosmological origin. The physics of fireball shock models is discussed, with attention to the type of light histories and spectra during the gamma-ray phase. The evolution of the remnants and their afterglows is considered, as well as their implications for our current understanding of the mechanisms giving rise to the bursts.

INTRODUCTION

The discovery of X-ray, optical and radio afterglows of gamma-ray bursts (GRB) amounts to a major qualitative leap in the type of independent observational holds on these objects. Together with existing γ -ray signatures, these provide significantly more severe constraints on possible models, and may indeed represent the light at the end of the tunnel for understanding this long-standing puzzle of astrophysics.

The report of long wavelength observations of GRB 970228 over time scales of days to weeks at X-ray (X), and months at optical (O) wavelengths (Costa et al. , 1997) was the most dramatic recent development in the field. In this and subsequent IAU circulars, it was pointed out that the overall behavior of the long term radiation agreed with theoretical expectations from the simplest relativistic fireball afterglow models published in advance of the observations (Mészáros & Rees, 1997a; see also Vietri, 1997a). A number of theoretical papers were stimulated by this and subsequent observations (e.g. Tavani, 1997; Waxman, 1997a; Reichart, 1997; Wijers, et al. , 1997, among others), and interest has continued to grow as new observations provided apparently controversial evidence for the distance scale, possible variability and the candidate host (Sahu et al. , 1997). New evidence was added when the optical counterpart to the second discovered afterglow (GRB 970508) yielded a redshift lower limit placing it at a clearly cosmological distance

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(Metzger et al. , 1997), and this was strengthened by the detection of a radio counterpart (Frail et al. , 1997; Taylor et al. , 1997) as well as evidence for the constancy of the associated diffuse source and continued power law decay of the point source (Fruchter, et al. , 1997)

This new evidence reinforces the conclusions from previous work on the isotropy of the burst distribution which suggested a cosmological origin (e.g. Fishman & Meegan, 1995). Observational material on this is provided chiefly by a superb data base (currently of over 1700 bursts in the 4B catalog) which continues being accumulated by the BATSE instrument, complemented by data from the OSSE and Comptel instruments on CGRO, as well as Ulysses, KONUS and other experiments. At gamma-ray energies, much new information has been collected and analyzed, relevant to the spatial distribution, the time histories, possible repeatability, spectra, and various types of classifications and correlations have been investigated. At the same time, investigations of the physics of fireball models of GRB have continued to probe the γ -ray behavior of these objects, as well as the afterglows. Much of the recent theoretical work has concentrated on modeling the time structure expected from internal and external shock models, multi-wavelength spectra, the time evolution and the spectral-temporal correlations.

THE DISSIPATIVE FIREBALL SCENARIO

The dissipative (or shock) fireball model is a fairly robust astrophysical scenario, independent of the particular type of progenitor, based only on the fact that it must inject the inferred large amount of energy inside the very small volume required by causality and the timescales characteristic of GRB (Rees & Mészáros , 1992, Mészáros & Rees, 1993). The observational and physical motivation for this generic scenario of GRB has been described in detail elsewhere (e.g. Mészáros , 1995). The very large energy deposition inside a small volume leads to characteristic photon energy densities which lead to an optically thick γe^\pm fireball that is highly super-Eddington. The resulting expansion must be highly relativistic ($\Gamma \sim 10^2 - 10^3$), in order to avoid having the observed 0.1-10 GeV photons degraded by photon-photon interactions, and to yield the right timescales and energies. The fireball initially is thermal, and converts most of its radiation energy into kinetic energy (bulk motion). This kinetic energy of motion must be tapped via some dissipation mechanism, which is most likely to be shocks, and these probably occur after the fireball becomes optically thin, as suggested by the nonthermal spectra.

The plasma, MHD and radiation physics involved in the fireball shock scenario are familiar, being used in a number of other astrophysical situations. The basic ingredients, such as a high Γ outflow, collisionless shocks, magnetic field generation at some fraction of equipartition, acceleration of electrons to a power law, efficient energy exchange between protons and electrons, etc. are common features (or common problems, to varying degrees) in AGN, pulsars winds and supernova remnants. In AGN and possibly pulsar winds, conditions qualitatively similar to those in GRB

seem to obtain, and these sources are known to have in many cases efficiencies of at least tens of percent in converting bulk kinetic energy into nonthermal particles and radiation. As in those sources, for GRB fireballs it is assumed that the fluid approximation is valid whenever the usual plasma kinetic theory criteria are satisfied, e.g. that the dimensions of the region are much larger than the proton gyroradius or the proton Debye length. The shocks serve to reconvert the kinetic energy of the outflow into random energy, and to accelerate relativistic particles which can radiate a power law spectrum. The cosmological fireball shock model appears to have received strong confirmation from the afterglow observations, and from the fact that many of the basic gamma-ray signatures can be understood within the framework of the model without undue parameter twisting.

The generic nature of this scenario stems from the fact that it is largely *independent* of the detailed nature of the primary energy release mechanism, whether it be a binary compact object merger (NS/NS or NS/BH, e.g. Paczyński 1986), a “failed Supernova Ib” (Woosley, 1992), a young ultrastrongly magnetized pulsar (Usov, 1992), a “hypernova” (Paczynski, 1997), etc. This is because the primary mechanism is initially enshrouded in an optically thick pair fireball, which washes out most of the details, the observed radiation being produced outside the pair photosphere. Some information, however, may be carried through, e.g. in the details of the light curve (especially if this is due to internal shocks, see below).

A major theoretical question is how the very large bulk Lorentz factors inferred from observations are produced. Neutrino-antineutrino annihilation leading to pairs (Eichler, et al. , 1989) have been proposed. Since the merger would lead also to enormous radiation pressure, a baryon rich outflow would however pollute the e^\pm, γ fireball, but a clean fireball might be achieved if tidal heating and annihilation occur before merger, or if enough annihilations occur around the centrifugally evacuated binary rotation axis (Mészáros & Rees, 1992). Numerical simulations using Newtonian potentials (Ruffert & Jahnka, 1997) indicate that this may not be straightforward, although effects like turbulent convection and magnetic fields could improve the pair luminosities. Matthews, et al. (1997) use a general relativistic hydro code and conclude that both NS collapse to black holes before merger, producing enough heating to power a pair luminosity comparable to required estimates. The disagreement between numerical simulation results is debated, and further refinements in models involving neutrino annihilation should be forthcoming.

On the other hand, magnetic fields may be responsible for a large or even dominant fraction of the relativistic stress tensor in the fireball. Super-strong magnetic fields are probably generated during the collapse of the rapidly rotating configuration (Usov, 1992, Mészáros & Rees, 1992, Narayan, et al. , 1992, Thompson, 1994, Vietri, 1997a), and this may contribute significantly to the energy density of the fireball. Such fields could in fact be dynamically dominant around the rotation axis, especially if the central objects collapses to a black hole, leading to a Poynting dominated outflow which could be almost baryon-free (Mészáros & Rees, 1997b). Magnetic fields would, of course, also ensure a high radiation efficiency. MHD numerical simulations are difficult, as in pulsar winds and AGN jets, and have not so

far been done. In any case, it is worth stressing that the motivation for high bulk Lorentz factor ($\Gamma \gtrsim 10^2$) outflows in GRB is largely observational, in particular the observation of 0.1-10 GeV photons, which are hard to explain otherwise (e.g. Harding & Baring, 1994).

GAMMA RAY TEMPORAL PROPERTIES AND SPECTRA

Two types of fireball models have been discussed, both of which produce the nonthermal spectrum via shocks occurring after the fireball has become optically thin, as inferred from the nonthermal nature of the spectrum. These involve different explanations for the typical duration of the burst, and predict different time variabilities. In the first type (a) (e.g. Mészáros & Rees, 1993) the shocks are those caused by interaction of the gaseous fireball ejecta with an external medium. In this case the typical duration is given by the Doppler delayed arrival of the light from the beginning and end of the ejecta shell, or from the delay between surface elements within the light cone. This assumes that any “intrinsic” burst duration is shorter than the above duration (impulsive approximation). Any “intrinsic” short time variability is washed out by the fact that radiation is received from a light cone and a finite width over which Γ varies by at least a factor 2. (The afterglows discussed below are well fitted, in their overall average features, by the late stages of an external shock).

In the second type of model (b) (Rees & Mészáros, 1994, Paczynski & Xu, 1994), the shocks leading to γ -rays are those which may be expected within the outflow itself, e.g. internal shocks caused by the catching up of faster portions with slower portions of the flow. These, if they occur, tend to do so at smaller radii than the previous external shocks, and the duration is likely to be given by the intrinsic duration of the energy release (since the Doppler delayed light arrival or light cone duration is likely to be shorter than the latter). One of the two stated purposes for introducing this model is that it *does* specifically allow arbitrarily complicated light curves (Rees & Mészáros, 1994), which are expected to reflect any “intrinsic” variability injected at the base of the outflow. These models are also referred to as wind models, or central engine models.

Detailed kinematical calculations (Fenimore, et al., 1996) show explicitly some of the constraints imposed by observations on external shock light curves. Sari & Piran (1997) showed analytically that external shocks in a blobby external medium would not be able to reproduce very complicated light curves with many subpulses, unless the efficiency is very low, $\lesssim 1\%$. Nonetheless, as shown by Panaitescu & Mészáros (1997a), if magnetic inhomogeneities are present or develop in the ejecta, and there is some pre-beaming in the comoving frame, one can get up to 5-10 peaks with good efficiency in an external shock light curve, and the spectral-temporal correlations are close to the observed values. For bursts with a very large number of subpulses, simulations of bolometric internal shock light curves (Daigne

& Mochkovich, 1997; Kobayashi, et al. , 1997) are in good qualitative agreement with the observations.

The nonthermal radiation spectrum of GRB is likely to be due to synchrotron or inverse Compton (IC) radiation of electrons or positrons accelerated in the optically thin shocks described above. Particles accelerated, e.g. by a Fermi type mechanism, in the presence of modest magnetic fields lead to nonthermal photon spectra similar to those observed (e.g. Mészáros , Rees & Papathanassiou, 1994 for impulsive shock spectra, and Papathanassiou & Mészáros , 1996 for wind spectra). Basically, two types of spectra are possible: those where the observed “break” in the 50 KeV - 2 MeV range is due to the synchrotron characteristic energy, or those where it is due to the IC upscattering of a lower energy break (typically at optical energies) which itself is due to synchrotron. The latter requires smaller magnetic fields and smaller electron minimum energies γ_m . Above γ_m shock acceleration is assumed to provide the electron power law responsible for the flattish νF_ν spectrum characteristic of bursts: an electron index $p \sim -3$ reproduces this well. The burst spectra can satisfy the X-ray paucity condition (i.e. the observation that generally $F_x \lesssim 3 \times 10^{-2} F_\gamma$ during the γ -ray burst), since below the break one expects a spectrum $\nu F_\nu \propto \nu^{4/3}$. On the other hand, spectra flatter than this can be easily obtained in an inhomogeneous magnetic field, or for a spatially varying bulk Lorentz factor, so that “soft excess” bursts can also be produced. In addition, one expects significant simultaneous emission at GeV energies, and modest but detectable simultaneous X-ray and optical emission (Mészáros & Rees, 1993b, Mészáros , Rees & Papathanassiou, 1994, Katz, 1994b, Papathanassiou & Mészáros , 1996). In addition, if GRB occur inside galaxies where the external medium has an appreciable density, one would expect internal shock bursts to be followed by external shock bursts, which can be relevant for, e.g. delayed GeV emission (Mészáros & Rees, 1994). In general one expects different spectral and temporal properties for such compound bursts. A study of the properties of internal shocks followed by external shocks (Papathanassiou, 1997) provides constraints on the internal parameters of the outflow (duration, variability timescale and luminosity) in different external environments.

One of the signs of the development of the subject is that γ -ray observations of GRB have become sufficiently detailed and extensive that they are beginning to probe questions of the internal physics of the models, such as the shock acceleration, the magnetic field equipartition fraction, and the radiative efficiency involved. As far as the specific radiation mechanism, Tavani (1996) has presented detailed synchrotron spectra calculated numerically with a distribution of shocked electrons produced by a specific diffusive acceleration mechanism, and these were fitted to a variety of observed γ -ray spectra. Another investigation (Cohen, et al. , 1997) aimed at testing the synchrotron hypothesis uses the fact that an electron distribution with a low energy cutoff would produce a low frequency asymptotic intensity spectrum with a slope of 1/3, while the time integrated high frequency slope would be expected to be -1/2, compatible with a sample of BATSE spectra studied by these authors. This issue remains under discussion, e.g. Crider, et al. ,

1997. The problem of a relatively high radiative efficiency during the γ -ray event is, clearly, one of the requirements of a fireball shock, or indeed of any other model. In particular, one needs to ensure that much of the energy carried in protons (if these are present and energetically dominant) is shared with the radiating electrons or pairs. Specific mechanisms have been proposed for this (Bykov & Mészáros, 1996). A high radiative efficiency is natural in models where magnetic fields are prominent (e.g. Narayan, et al., 1992, Usov, 1994, Thompson, 1994). The electron-proton exchange would also be obviated in the reverse shock for scenarios involving Poynting dominated outflows where the inertia is mainly due to pairs (Mészáros & Rees, 1997b), although in the late stages of deceleration the blast wave pushed ahead of the ejecta will unavoidably include baryons.

Another area of contact between models and observations is in the area of spectral-temporal correlations in the gamma-ray range. Fenimore & Sumner (1997) find that the observed spectral break energies decay in time faster than predicted from single shell analytic models. Crider, et al. 1997b argue that the evolution of the spectral break with integrated photon flux may be a restriction on simple models. Numerical hydrodynamic simulations (Panaitescu & Mészáros, 1997a) of external shock models indicate that many of the commonly observed correlations are well reproduced; among these are a brightness and hardness correlation, hardness and duration anti-correlation, a hard to soft evolution outside of intensity pulses, a break energy increasing with intensity during a pulse, the break energy decreasing with increasing fluence, earlier pulses being harder, pulses being narrower at higher energies, etc. This is a continuing area of activity.

THE IMPLICATIONS OF AFTERGLOWS

The breakthrough Beppo-SAX observation of GRB 970228 provided both a study of the long-term X-ray decay (extending over days) and an accurate localization permitting subsequent optical follow-ups (extending to months). The X-ray and optical sources are both point-like, as expected for a fireball at cosmological distances (dimension $\sim 0.1 - 1$ pc after \sim months). The spectra are nonthermal, as expected from the simplest model based on synchrotron radiation of shock-accelerated electrons from a decelerating shell interacting with an external medium (Mészáros & Rees, 1997a), and as predicted, it decays as power law in time with an index close to the expected value (see also Vietri, 1997a; Waxman, 1997a; Reichart, 1997; Sari, 1997). Furthermore, a fuzzy extended source was identified around the point source. While the initial optical magnitude of the point source decayed from ~ 20 to ~ 24 , there was uncertainty as to whether the diffuse source remained constant and whether it showed any proper motion (Caraveo, et al., 1997). However, the September 1997 HST images (Fruchter et al, 1997) have largely dispelled such doubts, indicating that the diffuse source remained at $m_R \sim 25.5$ with negligible proper motion, being compatible with a distant ($z \sim 1$), faint (possibly irregular) galaxy, while the optical point source is still present at $m_R \sim 28$, right along the

extrapolation of the earlier power law.

A major highlight was the detection of the afterglow of GRB 970508, which largely followed the pattern of GRB 970228, but which added considerable excitement because of new, even if not entirely unexpected, features. The most significant of these is that a redshift limit was obtained (Metzger, et al. , 1997) of $0.835 \leq z \lesssim 2.3$, based on several systems of absorption lines. Another previously unobserved phenomenon was that the optical flux of the point source initially rose as a power law, followed by a decay similar to that of GRB 970228. This, in fact, is what one expects from a cloud where the spectrum has a peak initially above optical frequencies that shifts downwards during its expansion (Katz, 1994b), and is in agreement with the Mészáros & Rees (1997a) simplest model. Another previously unobserved feature was the detection of a radio afterglow in GRB 970508, about a week after the outburst, peaking after weeks and then decaying slowly. With a self-absorption frequency around 5-10 GHz (overestimated in early calculations), this is also compatible with the 'simplest' model (e.g. Waxman, 1997b, Katz & Piran, 1997). Furthermore, scintillations in the radio spectrum, predicted by Goodman (1997), were also observed (Frail et al, 1997), providing a nice double-check on the physical dimension of the source of ~ 0.1 pc. An interesting, and less expected result is that the scintillation is of large amplitude and broad band, suggesting it is diffractive (Waxman, et al, 1997). This requires a small size, which comes from the fact that the intensity is concentrated in a ring of radial extent substantially smaller than the radius of the visible disk (Waxman, 1997c, Panaitescu & Mészáros , 1997b, Sari, 1997b). This is because for equal observer times one sees an egg-shaped region of the outflow and the portion around the edges corresponds to a younger, hence hotter and higher field, stage of the remnant. Another unexpected feature is that the optical light curve appears to have been steady or decaying for a brief (few days) initial period before it started to rise and then decay (Pedersen, 1997). One explanation for an initial decay could be that it is due to emission from a central jet, which later becomes overwhelmed by emission from a more energetic isotropic outflow at large angles (Mészáros , et al, 1997).

One issue is whether the fireball, as it slows down by sweeping increasing amounts of external matter, evolves with $\Gamma \propto r^{-3/2}$ as expected in the adiabatic limit, or as $\Gamma \propto r^{-3}$ as expected if the remnant is in the radiative regime (Rees & Mészáros , 1992). This would have consequences for the evolution of the afterglow (Vietri, 1997b, Katz & Piran, 1997). In the latter case, the remnant would evolve faster, and could reach the nonrelativistic regime sooner, even if after some time it becomes adiabatic, as it should. Physically, however, for the remnant dynamics to be 'radiative' implies that most of the kinetic energy in protons and fields has to be radiated in less than a dynamic time (Mészáros , et al. , 1997). This would require field reconnection, as well as efficient mechanisms for protons to re-energize electrons whose cooling timescale is shorter than the dynamical time in the cooling region (behind the shock front and throughout the remnant), and it is far from being understood how this would happen. In fact, the optical power law of GRB 970228 is unbroken so far, after 8 months, arguing for an early onset of the adia-

batic regime, and indicating that the nonrelativistic regime has not been reached yet (which is strong indication for a cosmological distance, Wijers et al, 1997). Another observational constraint comes from the radio scintillations in 970508: this requires a relatively small size \lesssim few 10^{17} cm, after a time of several weeks. The longitudinal size is $r \sim 4(2n+1)\Gamma_o^2 ct$ where $n = (3/2, 3)$ for an (adiabatic, radiative) remnant, but the ring structure of the remnant emitting region reduces somewhat the coefficient in front (Panaitescu & Mészáros, 1997b). The adiabatic behavior seems more in accord with observations (Waxman, 1997c). However numerical calculations of the light curve and spectral evolution (e.g. Panaitescu & Mészáros, 1997c) are needed in order to address this issue more thoroughly.

A question is why some bursts (e.g. GRB 970111) are detected in γ -rays but not in X/O, despite being in the field of view of Beppo-SAX. One reason may be that the γ -ray emission could be due to internal shocks (leaving essentially no afterglows [25]) and the environment has a very low density, so the external shock occurs at larger radii and over longer times than in “canonical” afterglows, resulting in a sub-threshold X-ray intensity. This may be the case if GRB arise from compact binaries which are ejected to considerable distances from the host galaxy, where the external density may be much lower than the typical ISM values. Low density environments may also occur if the GRB goes off inside a pulsar cavity inflated by one of the precursors in the binary. This give rise to a deceleration shock months after the GRB with a much lower brightness. Conversely, an interesting consequence of anisotropic models (Wijers et al, 1997; Rhoads, 1997; Mészáros, et al 1997) is that there could be a large fraction of detectable afterglows for which no γ -rays are detected. The outflow at large angles is certain to be more baryon-loaded, and therefore of lower Γ , so that the shocks would occur later and would be at longer wavelengths.

It is also possible that some bursts arise in unusually high density environments (such as a star-forming region, where failed supernova or hypernova progenitors may reside (Paczynski, 1997). This could lead to a more rapid onset of the deceleration leading to the X-ray phase, and it would also imply an increased neutral gas column density and optical depth in front of the source. A special case is that of GRB 970828, where X rays have been observed, but no optical radiation down to faint levels (Groot et al., 1997). The presence of a significant column density of absorbing material has been inferred from the low energy turnover of the X-ray spectrum (Murakami, et al., 1997), and the corresponding dust absorption may in fact be sufficient to cause the absence of optical emission (Wijers & Paczynski, private comm.). The difference between the low density and high density environments cases could be tested if future observations of afterglows reveal a correlation with the degree of galaxy clustering or with individual galaxies.

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